Gravitational Decoherence in the Lab?

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Introduction

- Decoherence is essential in the study of the quantum-to-classical transition.
- Origin lies in the fact that a general quantum system is continuously interacting and fundamentally inseparable from its environment.
- As the interaction continues, information about the system is lost to the environment causing properties such as superposition to be suppressed.
- System and environment become entangled, resulting in the system becoming increasingly mixed over time.
- Different models predict the decoherence process to occur over a rapid but non-zero time scale.

Various models of *gravitational* decoherence have been proposed, most notably by Penrose, Diosi, and Blencowe. While these models are each distinct in their own way, they all elevate gravitational phenomena to be the dominant proponent of decoherence in a quantum system. This project considers a system comprised of a superposed quantum particle interacting gravitationally with another non-superposed quantum particle. With the second particle acting as the environment, we then study the decoherence phenomena of the first particle.

Recent experimental progress has given rise to the possibility of performing experiments involving massive quantum systems in superposition. Specifically, the work of researchers such as M. Aspelmeyer et al. in the field of cavity optomechanics have suggested that massive levitated nano-objects can be used to generate superpositions of macroscopically distinct position states. Such advances have the potential to test different models of gravitational decoherence. The present work is a first step in bridging the gap between theory and experiment. The goals are to:

- Construct a simple quantum system and describe its evolution under gravitational interaction
- Simulate the reduced dynamics of subsystem of interest (i.e. trace out environment)
- Compute and analyze various measures of nonclassicality
- Connect analysis to real-world cavity optomechanics experiments

System Setup

We consider two quantum particles in one dimension separated by a distance R. One particle is initially in a spatial superposition of two Gaussian wave packets – the size of the superposition being Δ – while the other is initially a Gaussian state:

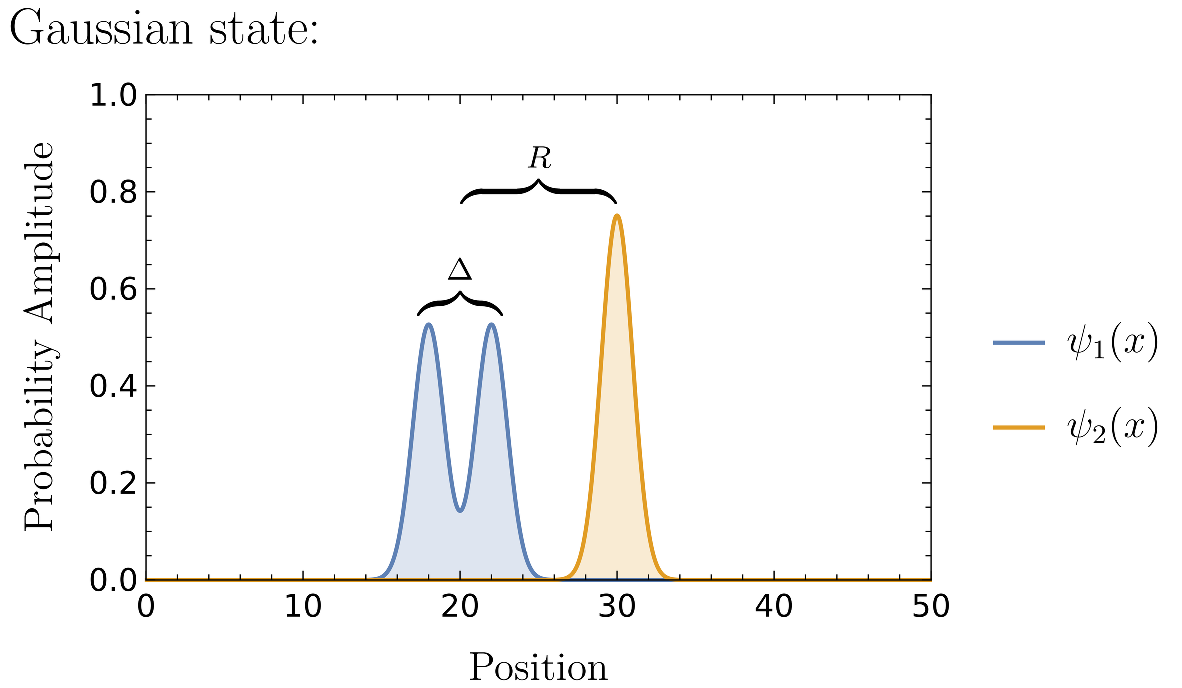

Figure 1: Initial spatial wavefunctions $\psi(x) = \langle x|\psi\rangle$ of the interacting particles.

Open System Dynamics

We consider the gravitational interaction between the two particles to be well modelled by 1-dimensional Newtonian gravity. As such, the corresponding Hamiltonian for this system is

$$\hat{H} = \frac{\hat{p}_1^2}{2m_1} + \frac{\hat{p}_2^2}{2m_2} + Gm_1m_2\,|\hat{x}_2 - \hat{x}_1|\,. \tag{1}$$

We are ultimately interested in the reduced dynamics of the superposed particle as a result of the influence from the second particle (i.e. the environment). With the initial states of particle 1 and 2 depicted in Fig. 1 given by $\rho_i(0) = |\psi_i(0)\rangle\langle\psi_i(0)|$ for $i = \{1, 2\}$, the reduced state of particle 1 at time t is

$$\rho_1(t) = \mathrm{Tr}_2\left[\hat{U}(t)\Big(\rho_1(0)\otimes\rho_2(0)\Big)\hat{U}^\dagger(t)\right] \tag{2}$$

where $\hat{U}(t)$ is the unitary operator generated by the Hamiltonian (1) and acts on the closed joint system $\rho_1(0)\otimes\rho_2(0)$. Fig. 2 shows the absolute values of the matrix elements of $\rho_1(t)$.

Behaviour of the Reduced Density Matrix $\rho_1(t)$

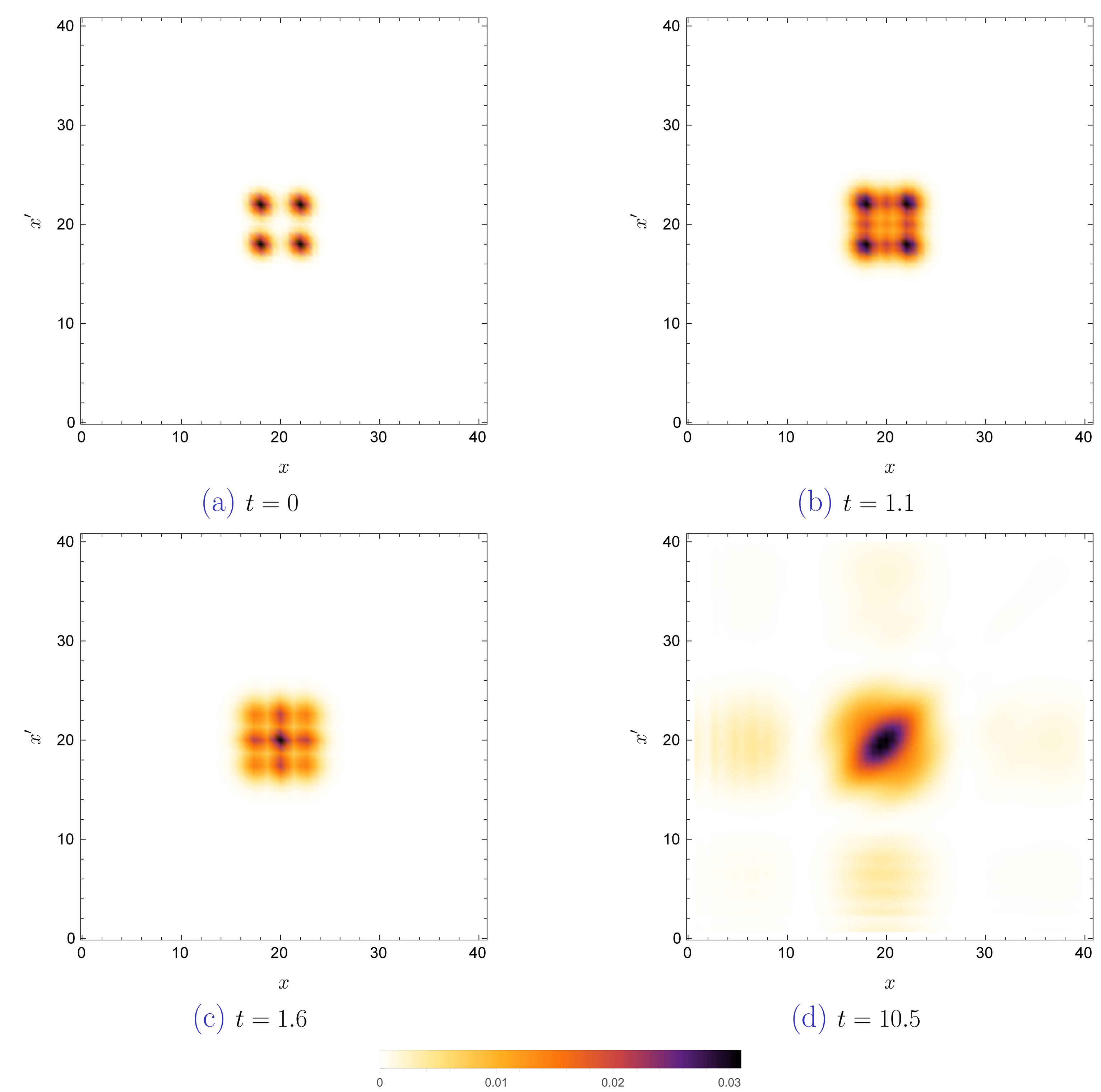

Figure 2: Magnitude of the reduced density matrix elements at four different times: $|\rho_1(x,x';t)|^2 = |\langle x|\rho_1(t)|x'\rangle|^2$

As a result of the gravitational interaction, we see that the superposition of particle 1 quickly becomes suppressed and the density matrix becomes increasingly mixed as the main contributions begin to form along the diagonal.

Purity

An interesting and useful measure of the nonclassicality of particle 1 is the purity

$$\mu(t) = \mathrm{Tr}\left[\rho_1^2(t)\right]. \tag{3}$$

Particle 1 is initially prepared in a pure state and thus has unit purity. However the evolution generated by eq. (1) entangles the two particles which results in decreasing purity of the reduced state $\rho_1(t)$ with time. Fig. 3 shows the purity of this reduced state as a function of time for different initial states of the two particles, specifically obtained by varying their separation R, the size of the superposition Δ, and their masses, m_1 and m_2. The initial wavefunctions depicted in Fig. 1 are

$$\psi_1(x) = N_1\left(\exp\left[-\frac{(x-\frac{\Delta}{2})^2}{2\sigma_1^2}\right] + \exp\left[-\frac{(x+\frac{\Delta}{2})^2}{2\sigma_1^2}\right]\right) \tag{4}$$

$$\psi_2(x) = N_2\exp\left(-\frac{(x-R)^2}{2\sigma_2^2}\right) \tag{5}$$

where N_1, N_2 are normalization constants.

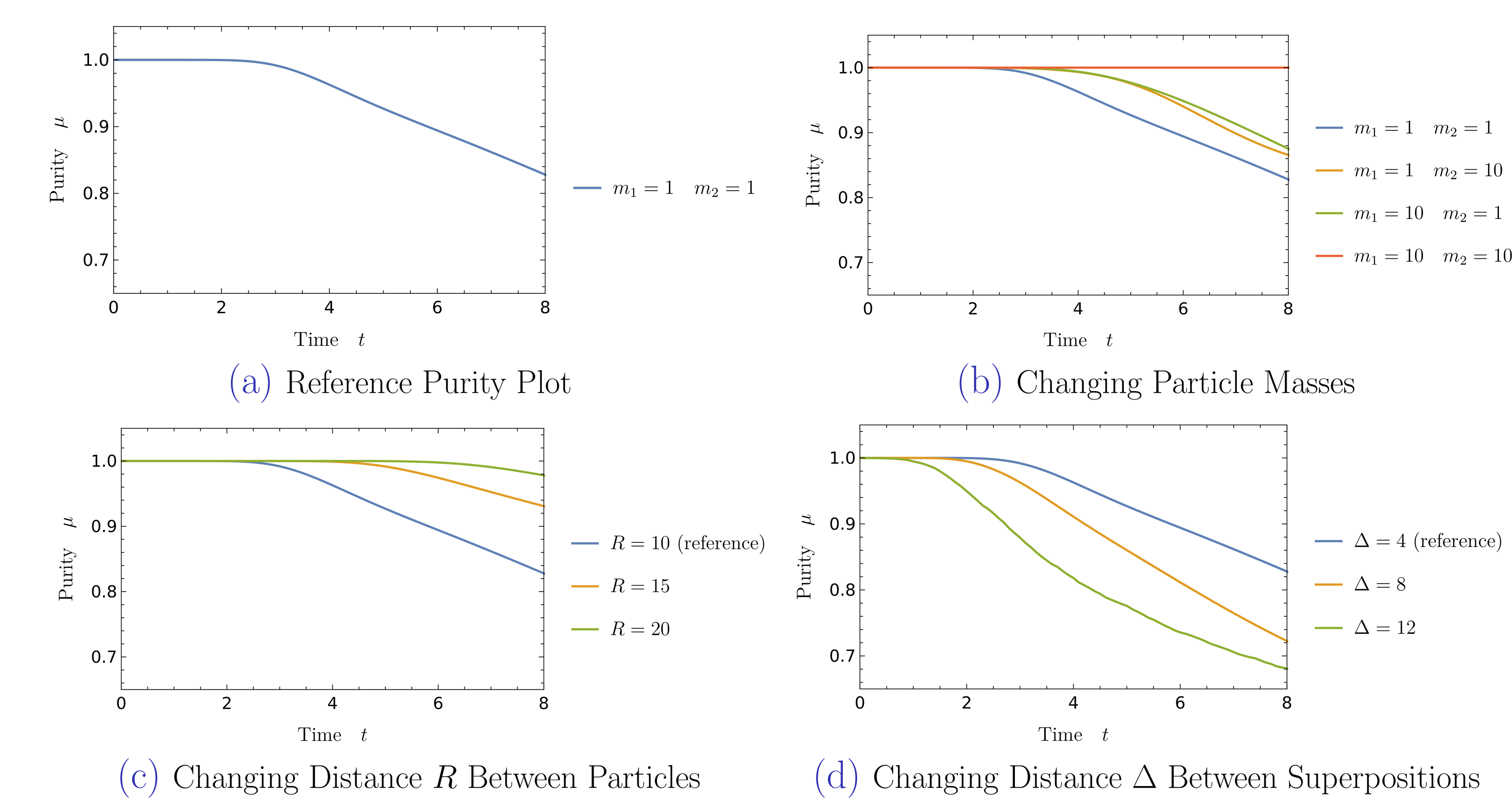

Figure 3: Purity of superposed particle as functions of time for different initial masses m_1 and m_2, separation R, and superposition size Δ.

Conclusions and Future Work

We find that gravitational interaction between two quantum particles induces decoherence. This manifests as the suppression of superposition and the decrease of state purity. We also observe that as a function of time, the purity

- Decreases at a slower rate as mass increases
- Decreases at a slower rate as initial separation distance increases
- Decreases at a faster rate as superposition size increases

The next step is to connect our model of gravitational decoherence with experiment. Specifically, we will focus on computing measures of nonclassicality that are experimentally relevant to recent work in cavity optomechanics.

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